

FIELD ADJUSTMENTS OF BED FORM PHASE DIAGRAMS

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Abstract Plane bed and symmetric dunes were found in Low Flow Conveyance Channel (LFCC), a narrow deep channel near Socorro, New Mexico that parallels the Middle Rio Grande. The ability to determine bed types in fluvial channels is important for estimating flow resistance and sediment and hydraulic modeling. The flow resistance and sediment transport can ultimately affect flood stage. Five sets of data are presented for flows ranging from about 400 cfs to about 1,550 cfs. Symmetrical dunes were found in four of the flows, and plane bed in the remaining data set.

Five bed form phase diagrams were selected to examine the stability fields of the LFCC dunes based upon stream power, shear stress, Froude number, mean velocity and a sediment mobility parameter. Two of the five diagrams could not be used because measured flow parameters exceeded the diagram values. The remaining three diagram predictions matched the measured bedform two out of five times for each data set. Thus the occurrence of these dunes is not well predicted by the current bed form phase diagrams. These data support the conclusion of Kostachuk and Villard (1996) that flume based bed form phase diagrams may not be “applicable to dunes in deep natural flows.” Laboratory models do not scale the same for sediment size, flow hydraulics and turbulence (Kostachuk and Villard, 1996), and results from such models may not be applicable to field conditions.

The ratio of dune height/length can be related to the equivalent roughness of Nikuradse (k'_s) (Van Rijn, 1982). The values of k'_s were estimated from the measured velocity profiles using the vertical velocity log law to estimate the dune height/length using the method of Van Rijn (1982), to compare with measurements. The dune height/length predicted by the method of Van Rijn (1982) only partially represented measured values. Differences between measurements and Van Rijn’s method are discussed.

INTRODUCTION

Bed features develop naturally in alluvial sand channels whenever the velocity of flow and shear stress exceed threshold values. These bed forms affect resistance to flow, sediment transport, turbulence, flood stage estimates, and velocity and depth for habitat characterization. Various authors have generally shown that dunes have an asymmetrical shape, with a long stoss side slope, sharp crest, short steep lee side slope, and lee side flow separation (Chien and Wan, 1999; Nelson and Smith, 1989, and Bennett and Best, 1995). Laboratory and field evidence also shows that dunes can be symmetrical with stoss and lee side slopes having approximately equal length, without flow separation (Sanderson and Lockett, 1983; Kostachuk and Villard, 1996; and Smith and McLean, 1997). Smith and McLean (1977) suggest that symmetrical dunes occur in situations where suspended sediment transport dominates so that suspended sediment settles on the lee side slope causing a more symmetrical shape. Due to the fact that incoming sediment supply could not be altered from river flows Smith and McLean (1977) suggestion could not be validated. Sanderson and Lockett (1983) also observed humpback dunes that have symmetrical

shape with a nearly flat dune crest. Several methods and diagrams have been developed, designed to predict the conditions under which plane beds, dunes, ripples and anti-dunes would occur. These bed phase diagrams are based mostly on flume data and may not be applicable to field conditions (Kostashuk and Villard, 1996). Secondary dunes can also be superposed on larger underlying primary dunes (Ashley, 1990; Harbor, 1998; Carling et al, 2000). The ratio of dune height/length can be related to the equivalent roughness of Nikuradse (k'_s) (Van Rijn, 1982). The objective of this paper is to summarize the LFCC bed form data, compare these data with published bed form phase diagrams, compare the measured k'_s with the method of Van Rijn (1982) and draw conclusions about the applicability of published methods to the LFCC. Suggestions are made about how to adjust the interpretation of the bed form phase diagrams to apply to the LFCC field channel.

Field Data Measurements of hydraulics, bed forms and sediment transport have been made on the straight reach of the Low Flow Conveyance Channel (LFCC) near Socorro New Mexico (Figure 1). Field tests were conducted during May or June of 1997, 1998, 1999, and 2001. The experimental program included measurements of bed material particle-size distribution, bed form, water surface slope as well as standard measurements of flow rate and cross sections. The bed form and some of the channel hydraulics portion of the experimental testing procedure are reported herein. Target discharges ranged from 300 cfs to 1,500 cfs. Cross-sectional shape of the channel is trapezoidal with riprap side slopes and a mobile sand bottom. The side slopes are about 2.2 horizontal to 1 vertical, and the riprap size is $D_{50}=152$ mm (6 in) and $D_{84}=250$ mm (9.8 in).

The LFCC discharges were controlled at the inlet works located at San Acacia Diversion Dam (Figure 1). Table 1 contains the cross-sectional averaged hydraulic parameters for the various data sets. The Manning's roughness coefficients (n values) were determined by matching the measured water surface elevations with those estimated in a HEC-RAS (USACOE, 2008) model. The hydraulic parameters reported in Table 1 were computed by HEC-RAS once the calibration was complete. The bed elevation in all of the dune bed data sets remained about the same with the water surface elevation increasing with discharge.

DATA ANALYSIS

Dune Data The LFCC dunes were symmetrical with stoss and lee sides of nearly equal for all LFCC measurements steepness (Figure 2). Humpback dunes with flat tops with equal steepness stoss and lee sides also occurred. The primary symmetrical and humpback dunes had average lengths from 630 to 890 ft. (Table 2). Primary dunes are on average 7 to 10 times longer than secondary dunes (Table 2). The length of the flat top on humpback dunes for primary dunes ranges from 110 to 360 ft. and for secondary dunes the range is 10-100 ft. Primary dune lengths were "very large" (dune length > 330 ft.) while dune heights ranged from the "small" ($0.25 < \text{dune height} < 1.3$ ft.) to "medium" ($1.3 < \text{dune height} < 2.5$ ft.) based on the classification of Ashley (1990). Secondary dunes lengths were "large" and the height was "small" or "medium" based on the classification. The stoss and lee side slope angles were less than 1 degree, while symmetrical dunes reported on the Rhine river had lee side slopes of about 10 degrees with some as low as 1-2 degrees (Carling, et al., 2000). Fraser river dunes had stoss and lee side angles ranging from 2.4 to 18.9 degrees (Kostachuk and Villard, 1996).

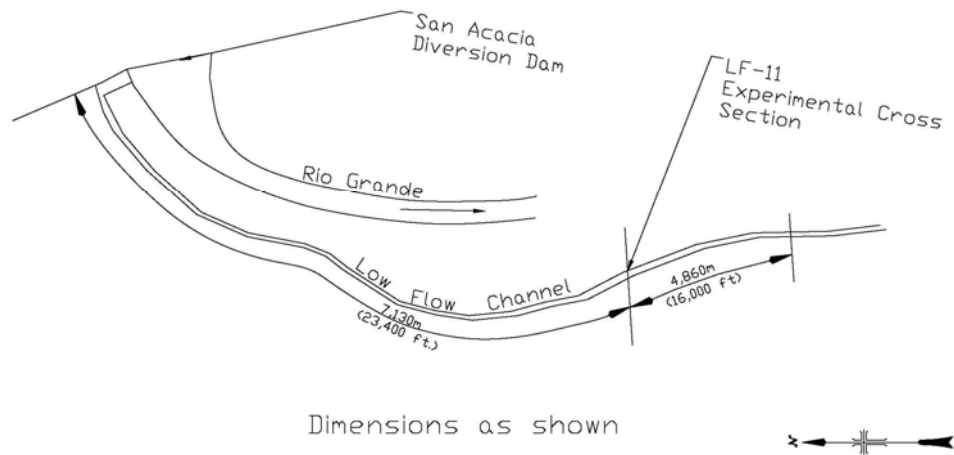


Figure 1 Plan view of the test reach

Dune symmetry ratio is defined as the stoss side length (L_s) divided by the lee side length (L_l). The majority of primary dunes had symmetry ratios ranging from 0.8 to 1.6 and secondary dunes had a symmetry ratio ranging from 0.8 to 1.4 (Figure 3), falling in the same range of symmetry ratios of symmetrical dunes found on the Fraser River (Kostachuk and Villard, 1996). No data sets were available to compare the symmetry ratios of primary dunes. By comparison, asymmetrical dunes on the Fraser River had symmetry ratios ranging from 5.67 to 8.17 (Kostachuk and Villard, 1996).

Five bed form phase diagrams were selected to examine the stability fields of the LFCC dunes: stream power diagram of Simons and Richardson (1963, 1966), shear stress diagram of Chabert and Chauvin (1963), Froude number diagram of Simons and Senturk (1992), mean velocity diagram of Ashley (1990), and the modified sediment mobility parameter diagram of Van den Berg and Van Gelder (1993). These five phase diagrams each have fundamentally different physical parameters to estimate bed form phases. Dunes were measured in all data sets except the 1999 data set, while the published stability field diagrams showed anti-dunes, upper regime plane bed, transition between lower and upper regime, transition between dunes and anti-dunes, and some dunes. A re-examination of the data reported by Baird (2006) showed that some stability field predicted dunes. The dunes measured in the 2001-300 cfs data set matched the prediction by Simons and Richardson (1963, 1966). In the Chabert and Chauvin's (1963) shear stress diagram and the velocity based method of Ashley (1990), the LFCC measured shear stress and flow depth exceeded the reported range of each method. The stability fields of Simons and Richardson (1963, 1966) predicts dunes for the 300 cfs (2001), and 600 cfs (2001) target flows (Table 3) which corresponds to measurements. Table 3 contains the parameters used by Simons and Richardson (1963, 1966) including bed material sizes which are repeated from Table 2 for

easy reference. The Simons and Richardson (1963, 1966) stability fields did not predict the measured bed forms for 600 cfs (1999), 1500 cfs (1998), and 1200 cfs (1997). Within the range of 0.15 to 0.21mm, median bed size does not appear to be an appreciable factor for matching measurement with predicted, while a median bed size of 0.65 does have an effect. Bed size is the main factor for the 1500 cfs (1998 target flow) predicting transition bed form instead of antidunes. For most of these data bed shear stress and velocity have a much greater impact on the predictions when compared to influence of bed material size.

Table 1 Hydraulic data for cross section LF-11. The measured flow is for the period during which the ADV and cross section measurements were made.

Year	Target Flow (cfs)	Measured Flow (cfs)	Mean Velocity (ft/s)	Flow Area (ft ²)	Wetted Perimeter (ft)	Hydraulic Radius (ft)	Hydraulic Depth (ft)	Main Channel Mean Depth (ft)
1997	1200	1191	4.36	259	52.98	4.86	5.3	7.63
1998	1500	1552	3.72	377	63.88	5.70	6.44	9.55
1999	600	625	3.41	202	52.69	3.95	4.03	5.04
2001	600	585	2.44	239	53.66	4.04	4.77	7.34
2001	300	390	1.96	158	45.2	3.66	3.81	5.48

Year	Target Flow (cfs)	Measured Flow (cfs)	Energy Slope	Froude Number	Manning's n	D ₅₀ of Bed Material (mm)	Bedforms
1997	1200	1191	0.000647	0.38	0.026	0.21	Dune
1998	1500	1552	0.000616	0.30	0.026	0.65	Dune
1999	600	625	0.000382	0.33	0.020	0.15	Plane
2001	600	585	0.000413	0.28	0.035	0.16	Dune
2001	300	390	0.000260	0.23	0.024	0.21	Dune

Year	Target Flow (cfs)	Measured Flow (cfs)	Top Width (ft)	Bottom Width (ft)	Top Width/Hydraulic Depth (ft)	Momentum Balance U* (ft/s)	Momentum Balance Bed Shear Stress (psf)
1997	1200	1191	48.8	20	9.2	0.318	0.196
1998	1500	1552	58.5	24	9.1	0.336	0.219
1999	600	625	50.1	16	12.43	0.220	0.094
2001	600	585	50.2	16	10.53	0.232	0.104
2001	300	390	42	16	11.15	0.175	0.059

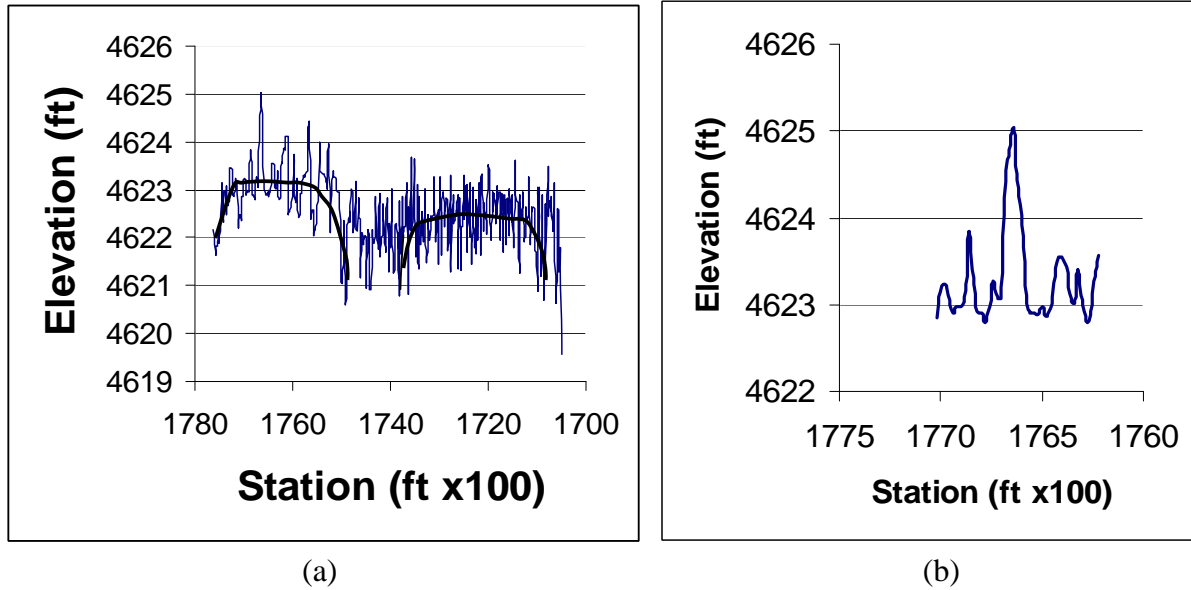


Figure 2 Dune Profiles (a) Primary Dunes (the black line denotes the approximate crest of the primary dunes) and (b) Secondary Dunes.

Table 2 Dune properties for 300, 600, 1,200, and 1,500 cfs discharges.

Date/Discharge	Average Dune Height/Length Ratio	Average Dune Height (ft.)	Average Dune Length (ft.)	Average Stoss Side Angle ($\sin^{-1}(H/L_s)$)	Average Lee Side Angle ($\sin^{-1}(H/L_l)$)
1997 1200 cfs					
Primary Dunes	0.00149	0.82	630	0.169	0.145
Secondary Dunes	0.00459	1.05	230	0.402	0.398
1998 1500 cfs					
Primary Dunes	0.0018	1.625	890	0.172	0.323
Secondary Dunes	0.0247	1.628	94	0.555	0.533
2001 600 cfs					
Primary Dunes	0.00583	2.78	730	0.515	0.413
Secondary Dunes	0.006978	0.767	111	0.458	0.454
2001 300 cfs					
Primary Dunes	0.00464	2.5	666	0.529	0.508
Secondary Dunes	0.01796	0.831	58	0.579	0.597

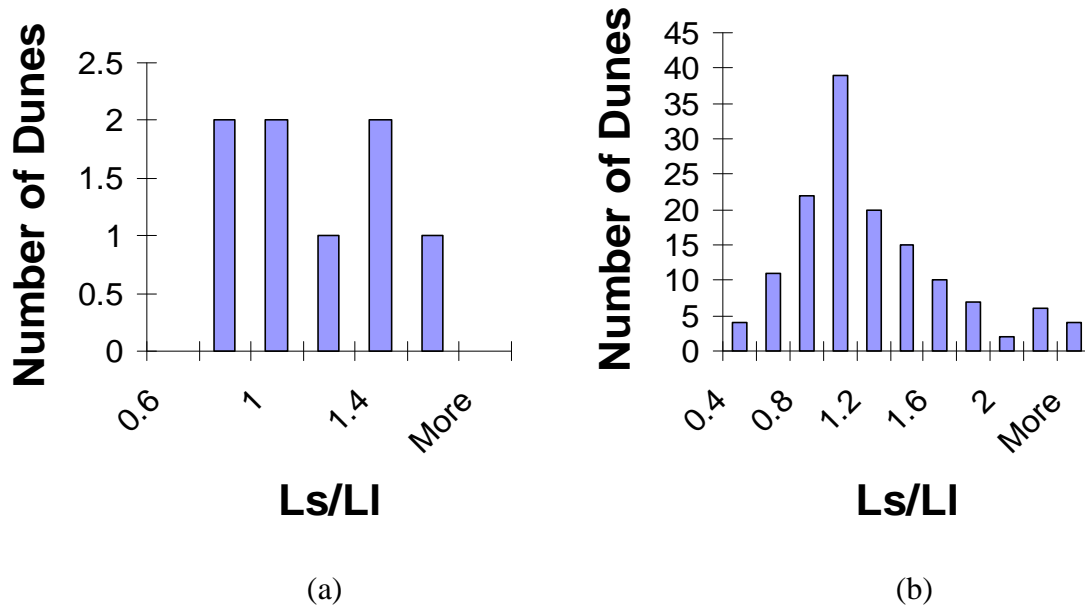


Figure 3 Dune Symmetry Ratio (a) primary dunes, and (b) secondary dunes.

Table 3. Bedform predictions compared to measured values using the stability fields of Simons and Richardson (1963, 1966)

Year	Target Flow (cfs)	Actual Flow (cfs)	Stream Power ($\tau_o V$) (lb/ft.s)	D ₅₀ of Bed Material (mm)	Measured Bedforms	Predicted Bedforms (Simons and Richardson (1963,1966))
1997	1200	1191	0.855	0.21	Dune	Anti-Dune and Plane Bed
1998	1500	1552	0.815	0.65	Dune	Transition
1999	600	625	0.321	0.15	Plane	Dune
2001	600	585	0.254	0.16	Dune	Dune
2001	300	390	0.116	0.21	Dune	Dune

The Simons and Senturk (1992) method was developed using canal and river data. This stability field prediction matches two measurements and the remaining three are transitional (Table 4). Inspection of the graph shows that the Rio Grande data used in part for developing this method is dune bed which plots in the transition and upper regime regions of the graph. This is very close to the same location on the graph as the LFCC data sets.

Van den Berg and Van Gelder (1993) developed a graphical relationship between the Shields parameter (dimensionless shear stress) and dimensionless particle size for flows over 1 meter deep. This method matches two measurements while the remainder is ripples (Table 5). Both the 1200 cfs (1997) and 1500 cfs (1998) target flow data sets have the same measured bed form as predicted.

Table 4. Bedform predictions compared to measured data using the stability fields of Simons and Senturk (1992)

Year	Target Flow (cfs)	Hydraulic Radius (ft)	D ₅₀ of Bed Material (mm)	D ₅₀ of Bed Material (ft)	Hydraulic Radius/Median Bed size (R/ D ₅₀)	Froude Number	Bedforms (Measured)	Bedforms (Simons and Senturk (1992))
1997	1200	4.86	0.21	0.00069	7100	0.38	Dune	Transition
1998	1500	5.70	0.65	0.00213	2700	0.30	Dune	Dune (Lower Regime)
1999	600	3.95	0.15	0.00049	8000	0.33	Plane	Transition
2001	600	4.04	0.16	0.00052	7700	0.28	Dune	Border between Transition and Dune (Lower Regime)
2001	300	3.66	0.21	0.00069	5300	0.23	Dune	Dune (Lower Regime)

Table 5. Bedform predictions compared to measured data using the stability fields of van den Berg, and van Gelder (1993) for flows deeper than 1 m (3.2 ft.)

Year	Target Flow (cfs)	Actual Flow (cfs)	Momentum Balance Bed Shear Stress (psf)	D ₅₀ of Bed material (mm)	Shields Parameter	Dimensionless Particle Diameter	Bedforms (Measured)	Predicted Bedforms using Van den Berg, and van Gelder (1993)
1997	1200	1191	0.196	0.21	0.28	5.30	Dune	Dune
1998	1500	1552	0.219	0.65	0.10	16.40	Dune	Dune
1999	600	625	0.094	0.15	0.19	3.78	Plane	Ripples
2001	600	585	0.104	0.16	0.20	4.04	Dune	Ripples
2001	300	390	0.059	0.21	0.08	5.30	Dune	Ripples

Kostachuk and Villard (1996) caution that flume based bed form phase diagrams may not be applicable to dunes in deep natural flows. Laboratory models do not scale the same for sediment size, flow hydraulics and turbulence (Kostachuk and Villard, 1996), and results from such

models may not be applicable to field conditions. Regardless of the interpretation of these results, it is apparent that published bed form phase diagrams cannot be readily applied to the LFCC data set.

Equivalent Roughness of Nikuradse (k'_s) Using the log law given as

$$\frac{\bar{u}}{u_*} = \frac{1}{\kappa} \ln\left(\frac{y}{y_o}\right) \quad (1)$$

where \bar{u} is the time average velocity at depth y , u_* is the shear velocity, κ is the Von-Karman parameter, and y_o is the zero velocity roughness height. The slope of the logarithmic portion of the stream wise velocity profiles was used to obtain the values of shear velocity u_* and the zero velocity roughness height y_o . By regressing u on to $\ln y$ the zero velocity roughness heights (y_o) (Bergeron, and Abrahams 1992) is found from

$$u = m \ln y + c \quad (2)$$

$$y_o = e^{(-c/m)} \quad (3)$$

where m is the regression line slope, and c is the intercept. The grain roughness height is found using (Julien, 1995)

$$k'_s = 30.2 y_o \quad (4)$$

where k'_s is the equivalent grain roughness height. For dune beds, Van Rijn (1982) developed an empirical equation for estimating k'_s using dune length and height

$$k'_s = 1.1H(1 - e^{-25H/L}) \quad (5)$$

applicable in the range $0.01 \leq H/L \leq 0.2$. The majority of the LFCC data has H/L values less than this range except the secondary dunes in 1998 at 1500 cfs and in 2001 at 300 cfs, and somewhat compares with the method of Van Rijn (1982) (Table 4).

Table 4. Comparison of Predicted and measured.

	H/L predicted by Van Rijn (1982)	Measured H/L
1998 1500 cfs Secondary Dunes	0.0219	0.0247
2001 300 cfs Secondary Dunes	0.0279	0.01796

CONCLUSIONS AND RECOMMENDATIONS

It has been shown that dunes on the LFCC are symmetrical shaped with long, low height geometry that sometimes have flat or humpback crests. LFCC bed forms are only partially predicted by the existing bedform phase diagrams and the equivalent grain roughness height for dunes is somewhat represented by the method of Van Rijn (1982). One possible explanation is that the dunes on the LFC are characterized as ranging from small to medium height dunes with long lengths (Ashley, 1990). It is likely that small dunes have a lower resistance to flow than larger dunes resulting in larger velocity causing the predicted bed forms to be upper regime or transition while dunes were measured. Adjusting the graphs to these data would mean that the line separating upper regime from lower regime dune beds would need to be raised (increasing dimensionless shear stress, Froude number, or stream power). One potential procedure for estimating bed forms in the field is to perform measurements. Then the location of the measurements in each method can be applied to future similar hydraulic and bed sediment size conditions. The method developed by Simons and Senturk (1992) using river and canal data provides the closest match between field data and predicted. On the Simons and Senturk (1992) bed form stability graph Rio Grande and LFCC dunes are found in the upper regime region of the plot.

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